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User's Manual for Axisymmetric Diffuser Duct (ADD) Code

Volume III—ADD Code Coordinate Generator

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and D. E. Edwards
United Technologies Research Center

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MINS: /* COMPUTER SYSTEMS PROGRAMS/ DUCTED FLOW/ FLUID FLOW/ SUBROUTINES

ABA: Author

ABS: This User's Manual contains a complete description of the computer codes known as the Axisymmetric Diffuser Duct (ADD) code. It includes a list of references which describe the formulation of the ADD code and comparisons of calculation with experimental flows. The input/output and general use of the code is described in the first volume. The second volume contains a detailed description of the code including the global structure of the code, list of FORTRAN variables, and descriptions of the subroutines. The third volume contains a detailed description of the CONDUCT code which generates coordinate systems for arbitrary axisymmetric ducts.

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USER'S MANUAL FOR
AXISYMMETRIC DIFFUSER DUCT
(ADD) CODE

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10.0 OPERATION OF CDUCT CODE

10.1 Runstream

The following runstream for a UNIVAC 1100 operating system is used to assign input/output disc files and to execute the CDUCT coordinate generator code.

```
@ASG,A      FILE9.,D/0/TRK/300000
@USE        9.,FILE9.
```

```
@ASG,A      FILE10.,D/0/TRK/300000
@USE        10.,FILE10.
```

```
@XQT        CDUCT
```

```
.
```

```
.
```

```
.
```

```
data cards
```

```
.
```

```
.
```

```
@FIN
```

FILE9 contains the coordinate data for a uniform mesh and FILE10 contains the data for a nonuniform mesh.

10.2 Input Format

The input format for the CDUCT code is described on the input data coding forms which follow. With the exception of the first card (Title card) and the duct geometry cards, the input data cards follow in sets of three cards. The first of three is a blank separator card. The second of three is the input variable name and the third of three is the value of the input variable. In general the input data is read as follows:

Card 1	Title Card
Cards 2-4	Program Control Parameters
Cards 5-7	Program Control Parameters
Cards 8-10	Coordinate Generator Parameters
Cards 11-13	Coordinate Generator Parameters
Card 14	Number of duct geometry coordinates
Cards 15 +	Duct geometry coordinates

PRODUCT CODE INPUT

Card 1 Title Card (18A4)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
TITLE																																																																															

MAXIT Maximum number of iterations for conformal mapping solution

- = 0 Print only input and final mapping
 - = 1 Print iteration results
 - = 2 Print approximate solution

ICORD Coordinate generation option:

- = 0 Calculate conformal mapping only
= 1 Calculate coordinates

NIPOT Approximate solution option

- = 0 Program determines number of approximate potential lines
> 0 User specifies number of approximate potential lines

Step control in approximate solution calculations

ECONV Convergence criterion on conformal mapping iteration

CØDUCT CODE INPUT

Cards 5-7 Program Control Parameters (T8, I1, T18, I3, T30, I3)

IESTIM Approximate solution option

= 0 Calculate approximate solution only
= 1 Calculate conformal mapping

KN Number of streamlines to generate on uniform grid, number of integration steps

NSD Potential line integration step control:

= 0 KN integration steps are used
> 0 There will be NSD additional steps taken for each of the KN steps yielding
NNS = (KN - 1) *NSD + KN total steps

CØDUCT CODE INPUT

Cards 8-10 Coordinate Generation Control Parameters (T6, I3, T18, I3, T30, I3, T44, I1, T51, E8.3, T68, I1)

JL Number of streamwise stations to output

JLPTS Number of data points to output from smooth

KL Number of nonuniformly spaced streamlines

IGRID Grid option

= 0 KN uniformly spaced streamlines output to unit IUUNIT
= 2 KL nonuniformly spaced streamlines output to unit INUNIT
= 1 Both meshes (0), (2) output

LOP Control option for mesh distortion

DDS Ratio of uniform/nonuniform mesh size at wall

CODUCT CODE INPUT

Cards 11-13 Coordinate Generation Control Parameters (T7, I2, T19, I2, T32, I1, T43, I2, T55, I1)

IUUNIT Output unit number for uniform mesh

INUNIT Output unit number for nonuniform mesh

I SMOOT Smoothing option

-11-

= 0 No coordinate smoothing

= 1 Smooth data using IMSL routine ICSVKU

JXK Number of knots to use in spline smoothing

CONDUCT CODE INPUT

Card 14 Number of Duct Geometry Coordinates (I3)

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

NLF

Number of coordinate pairs defining the upper/lower walls

CØDUCT CODE INPUT

Cards 15 → Duct Geometry Coordinates (8F10.6)

XU(1)	XU(2)	XU(3)	XU(4)	XU(5)	XU(6)	XU(7)	XU(8)
-------	-------	-------	-------	-------	-------	-------	-------

XU Upper wall x-coordinates

YU Upper wall y-coordinates

XL Lower wall x-coordinates

YL Lower wall y-coordinates

Where the data is read as follows

```
READ (IRUNIT,40) (XU(J), J=1,NLF)
READ (IRUNIT,40) (YU(J), J=1,NLF)
READ (IRUNIT,40) (XL(J), J=1,NLF)
READ (IRUNIT,40) (YL(J), J=1,NLF)
```

40 FORMAT (8F10.6)

10.3 Output Format

The printed output from the CDUCT code is given on the following pages and is largely self explanatory. These pages contain the names of the subroutines which calculate the data as well as any print options which may be involved.

Input Data Echo Page (1)

Printed by RCNTRL
Calculated by RCNTRL
Options None

Description

Subroutine RCNTRL reads the input control data (cards 1-13) and prints the input control data.

Duct Coordinates Echo Page (2)

Printed by CORINP
Calculated by N/A
Options None

Description

Subroutine CORINP reads the duct wall coordinates as described in Section 10.2 and prints the wall coordinates.

Pages 1-2 ----- INPUT WALL COORDINATES -----

Heading	Variable	Description
PT#	J ,	Wall coordinate number
XU	X _U ,	Upper wall input X coordinate
YU	Y _U ,	Upper wall input Y coordinate
XL	X _L ,	Lower wall input X coordinate
YL	Y _L ,	Lower wall input Y coordinate

Smoothed Duct Wall Coordinate Page (2)

Printed by CORINP
Calculated by SMARCL, SMOOTH
Options ISMOOT
ISMOOT = 0, no smoothing, no printout
ISMOOT = 1 smoothed, printed

Description

The input coordinates are read in CORINP and subroutine SMARCL is called to cubic-spline smooth the wall data.

Pages 1-2 ----- SMOOTHED WALL COORDINATES -----

Heading	Variable	Description
PT#	J	, Smoothed wall coordinate number
XU	X _U	, Smoothed upper wall X coordinate
YU	Y _U	, Smoothed upper wall Y coordinate
XL	X _L	, Smoothed lower wall X coordinate
YL	Y _L	, Smoothed lower wall Y coordinate

Calculated Duct Geometry Parameters (1)

Printed by MDAVIS, ROTATM
Calculated by MDAVTS, ROTAIM
Options None

Description

Subroutine MDAVIS determines the orientation of the duct and forces the inlet walls parallel. The rotational and scaling constant M and the exit wall angle are calculated and output by subroutine ROTATM.

Page 1 ----- CALCULATED DUCT GEOMETRY PARAMETERS -----

Heading	Variable	Description
None	θ_1	Angle of inlet lower wall to horizontal
None	h	True height of duct - perpendicular distance from lower wall to upper wall
None	M	Rotational and scaling constant used in Schwartz-Cristoffel mapping
None	α_E	Relative angle at exit of duct + π

Approximate Potential Flow Page (6)

Printed by WALLV, ESTIMP
Calculated by ESTIMP, ESTCOR, WALLV
Options IPRINT
 IPRINT < 2 no output
 IPRINT = 2 output

Description

Subroutine ESTIMP solves for a geometric approximate potential solution in the duct using subroutine ESTCOR to determine the positions of a set of approximate potential lines. The wall velocities and curvatures at the end points of these lines are calculated and printed by subroutine WALLV. The solution along each wall is interpolated to the set of wall coordinates and an estimate of the Schwartz - Cristoffel mapping is determined. This estimate is calculated and printed by subroutine ESTIMP.

Page 1 LOWER WALL ESTCOR FLOW ESTIMATE

Heading	Variable	Description
PT#	NP	Approximate potential line number
ARCL	S	Arc Length
VMEAN	\bar{V}	Duct midline velocity
VWALL	V_L	Lower wall velocity
KMEAN	K	Duct midline curvature

Approximate Potential Flow Pages (Cont'd)

Page 2

UPPER WALL ESTCOR FLOW ESTIMATE

Heading	Variable	Description
PT#	NP	Approximate potential line number
ARCL	S	Arc length
VMEAN	\bar{V}	Duct midline velocity
VWALL	V_u	Upper wall velocity
KMEAN	K	Duct midline curvature

Pages 3-4

LOWER WALL POTENTIAL FLOW ESTIMATE

Heading	Variable	Description
PT#	J	Wall coordinate number
VWALL	V_L	Lower wall velocity
KWALL	K_L	Lower wall curvature
TT	t	t-plane pole estimates
B	b	ζ -plane pole estimates

Pages 5-6

UPPER WALL POTENTIAL FLOW ESTIMATE

Heading	Variable	Description
PT#	J	Wall coordinate number
VWALL	V_u	Upper wall velocity
KWALL	K_u	Upper wall curvature
TT	t	t-plane pole estimate
B	b	ζ -plane pole estimate

Iteration History Pages

Printed by MDAVIS
Calculated by MDAVIS, STEP
Options IPRINT
 IPRINT = 0 not printed
 IPRINT > 0 history printed

Description

The current estimate of dz/dt is integrated along the duct walls in subroutine MDAVIS by steps $t_{j+1} - t_j$ in the t -plane. The results of the integration and the error of the current iteration are printed.

Page 1 ITERATION HISTORY

Heading	Variable	Description
PT#	J	Wall coordinate number - j
TX	t_x	Real component of t_j
<td>t_y</td> <td>Imaginary component of t_j</td>	t_y	Imaginary component of t_j
X	z_x	Real component of z_j
Y	z_y	Imaginary component of z_j
RATIO	R	Arc length ratio
ERROR		Absolute error $Z_{cj} - Z_j$
DZDT	$\frac{dz}{dt}$	Complex derivative of mapping

Iteration Summary Page (1)

Printed by MDAVIS, CLOSUR
Calculated by MDAVIS, CLOSUR
Options None

Description

Subroutine MDAVIS calculates the maximum relative error in the coordinate calculation for each iteration and tests for convergence of the mapping solution. Subroutine CLOSUR determines the integrated closure error of the solution.

Page 1 -----

-----ITERATION SUMMARY-----

Heading	Variable	Description
ITERATION	v	, Iteration count
SCALED MAXIMUM ERROR	ϵ_m	, Maximum scaled error for the iteration
None	ZCL	, Closure error $ \bar{Z}_1 - \bar{Z}_2 $
None	\bar{Z}_1	, Integration path #1 endpoint
None	\bar{Z}_2	, Integration path #2 endpoint

Mapped Duct Coordinate Page (2)

Printed by MDAVIS
Calculated by MDAVIS
Options None

Description

Once the mapping iteration has terminated, the final solution and errors are printed for each wall coordinate.

Pages 1-2 ----- MAPPED DUCT COORDINATES -----

Heading	Variable	Description
TX	t_x	Real part of t-plane pole location
TY	t_y	Imaginary part of t-plane pole location
X	X	Image of T under mapping
Y	Y	
XC	X_c	Input coordinates
YC	Y_c	
EX	ϵ_x	Error $ X - X_c $
EY	ϵ_y	Error $ Y - Y_c $
S	S	Arc length

Mesh Generation Page (1)

Printed by COORD
Calculated by COORD
Options None

Description

The t-plane uniform mesh that is used for the coordinate generation is described.

Page 1 ----- MESH PARAMETERS -----

Heading	Variable	Description
None	JL	Number of streamwise steps
None	DSTEP	Streamwise step size
None	KN	Number of uniform normal steps

10.4 Diagnostics and Failure Modes

Numerous checks are performed during the course of the calculation. If a non-fatal or correctable error occurs a DIAGNOSTIC message is printed and the calculation continues. If a fatal error occurs a FAILURE Mode error is printed and the calculation stops. A DIAGNOSTIC message is printed of the form:

- ** DIAGNOSTIC NO. XX for 2-D COORDINATE OPERATOR and a FAILURE Mode message is of the form:
- ** FAILURE NO. XX for 2-D COORDINATE GENERATOR where XX refers to one of the conditions listed below.

DIAGNOSTICS

- 1) NUMERICAL SOLUTION OF SCHWARTZ-CRISTOFFEL TRANSFORMATION FAILED TO CONVERGE

This error is detected in subroutine MDAVIS. It indicates that the scaled maximum error in the computed wall coordinates is greater than the input value ECONV after MAXIT iterations have been completed. By examining the ITERATION SUMMARY printed above the diagnostic message, one of three courses of action may be determined.

- a) The Scaled Maximum Error (SME) appears to be converging. Reset MAXIT and rerun the case.
 - b) The SME has converged to a value different than zero. This can often be remedied by increasing the number of sub-steps (NSD), employed in the normal direction integration. If this does not solve the problem, more wall definition coordinates may be needed.
 - c) The SME is not converging. This often indicates that a poor initial potential flow solution was generated.
- 2) UPPER AND LOWER WALLS NOT PARALLEL AT INLET. UPPER WALL FORCED PARALLEL TO LOWER WALL

This error is detected in subroutine ROTATM. It implies that the inlet upper and lower wall angles with respect to the horizontal differed by less than ten degrees but greater than 1.0-10. The upper wall endpoint is moved to force the walls parallel.

FAILURE MODES

- 1) MESH DISTORTION PARAMETER EQUALS = XXXXX

This error is detected in subroutine ROBRTS.

2) MESH DISTORTION PARAMETER EQUALS = XXXXX

This error is detected in subroutine DROBRT.

3) LOWER WALL ANGLE = XXXXX DEGREES

UPPER WALL ANGLE = XXXXX DEGREES

WILL NOT FORCE PARALLEL IF DIFFERENCE IS > 10 DEG.

This error is detected in subroutine ROTATM. It indicates that the inlet walls are not sufficiently parallel, and the program will not force the walls parallel to avoid drastically changing the geometry.

4) DEGENERATE DERIVATIVE MAPPING FOR I = XXXXX

This error is detected in subroutine MDAVIS. It implies that $|\frac{dz}{dt}| < 1.D-8$ at wall point XXXXX.

5) INCONSISTENT OR INVALID INPUT

This error is detected in main program CODUCT.

Check input data set.

6) READ ERROR ENCOUNTERED IN SUBROUTINE CORINP

This error, detected while reading duct wall coordinates, indicates an error in the input data set.

7) NUMBER OF INPUT POINTS EXCEEDS MAXIMUM (XXX)

This error, detected in subroutine CORINP, indicates that too many wall values are defined.

8) UNABLE TO COMPLETE APPROXIMATE SOLUTION

This error is detected in subroutine ESTCOR. It implies that more than ten attempts have been made to compute a single potential line and is usually due to very large wall curvatures.

9) INDEPENDENT STEP SIZE TOO SMALL

This error is detected in subroutine DERIV3. It indicates that two consecutively numbered wall coordinates are equal.

10) IMSL LIBRARY ICSVKU FAILURE NO. XXX

This error is detected in subroutine SMOOTH. It implies that the IMSL program ICSVKU cannot solve the spline problem. See IMSL manual to determine remedy.

11.0 GLOBAL STRUCTURE OF CDUCT CODE

This section of the manual is intended for the special user who wishes to modify the CDUCT code or adapt to a different computer. The section provides a global overview of the code in terms of the principal tasks. These tasks are clearly labeled in the main program CDUCT and agrees with the tasks listed on the Global Tree Structure Chart in Section 11.2. The global variables in labeled COMMON blocks are given in Section 11.3. Only the variables unique to the CDUCT code are listed. Variables that are used by both the CDUCT code and ADD code are listed in Section 6.0. Special problems associated with machine specific code are similar to those in the ADD code and are treated in Section 5.0.

11.1 Main Program CODUCT

Object

Main program for coordinate generator.

Options

IXFG	= 0	Full solution
	= 1	Interpolate only
IESTIM	= 0	Approximate solution only
	= 1	Schwartz-Cristoffel transformation also
ICORD	= 0	No coordinate output
	= 1	Coordinate output to disk files.

Theory

The control program CODUCT first calls subroutine RCNTRL (See Table 1) to read the user-input control parameters and options. Subroutine CORINP is then called to read the duct wall coordinates and, if requested, will smooth the wall coordinate using a cubic-spline fitting algorithm. Subroutine ESTCOR is called to geometrically determine the approximate potential flow solution necessary to start the conformed mapping iteration procedure. Then Davis' algorithm to compute the Schwartz-Cristoffel transformation is invoked by calling subroutine MDAVIS. Finally, subroutine COORD is called to generate and output the coordinate mesh parameters to disk file(s).

11.2 Global Tree Structure By Task

Read Control Input				
CODUCT	RCNTRL			
Read and Smooth Duct Wall Data				
CODUCT	CORINP	SMARCL	ARCL1 SMOOTH	ICSVKU
Calculate Approximate Potential Flow Solution				
CODUCT	ESTIMP	ARCL1 KURVTR ESTCOR WALLV	DER1V3 INSECT CROSS1 DER1V3 SUNBAR UNBAR	CROSS1
Calculate Schwartz-Cristoffel Transformation				
CODUCT	MDAVIS	ROTATM INTNOR STEP TTUP CLOSUR	STEP STEP INTNOR INTSTR	STEP STEP

Calculate Coordinates and Metrics						
CODUCT	COORD	CONSTR COOR1D	CDS	STEP	INSECT	CROSS1
			ROBRTS DROBRT NORLIN STRSTP CDVDN CORSTR Q2INTP BLKWRT QPSTOR STRSTP CDVDN CORSTR QPSTOR Q2INTP BLKWRT QPSTOR			
		COORMD	NTRAN\$ QPCURV STEP	NTRAN\$ QPCURV	INSECT	CROSS1

Transform from Uniform to Non-uniform mesh						
CODUCT	XFGRID	INITQ CONSTR BLKRED Q2INTP QPSTOR BLKWRT	BLKRED	NTRAN\$ INSECT	CROSS1	
			NTRAN\$ QPCURV NTRAN\$			

11.3 List of Labeled COMMON Blocks

<u>Name</u>	<u>Object</u>
BSMOTH	Variables for spline smoothing
CESTP	Variables for approximate solution
CORC0	Control options and parameters
CORT	Complex coordinates and derivative
IPDAVS	Complex solution variables
NSDAVS	Constants and parameters for mapping
OPDAVS	Intermediate Schwartz-Christoffel variables
TITLE	Run Title

List of Variables in COMMON/BSMOTH/
Variables for Spline Fitting

Name	Symbol	Length	Type	Description
A		NXK	R*4	Integration constant
B		NXK	R*4	Integration constant
CK		ICK,3	R*4	Spline coefficients
WK		IWK	R*4	Work area
XK		NXK	R*4	Knot locations
YPP		NXNTD2	R*4	Second derivative of input curve

List of Variables in COMMON/CESTP/
Variables for Approximate Solution

Name	Symbol	Length	Type	Description
HT	h_t	NXNTD2	R*4	Approximate duct height
IL, IU		NXNTD2		Index lower/upper walls
KKL, KKU	K_L, K_U	NXNTD2	R*4	Curvature lower/upper walls
KMEAN	\bar{K}	NXNTD2	R*4	Curvature of mean line
SL, SU	S_L, S_U	NXNTD2	R*4	Arc length lower/upper walls
SLI, SUI	S_{LI}, S_{UI}	NXNTD2	R*4	Arc length lower/upper walls
SMID	\bar{S}	NXNTD2	R*4	Arc length mean line
TH	θ	NXNTD2	R*4	Angle of mean line with x axis
VL, VU	V_L, V_U	NXNTD2	R*4	Velocity lower/upper walls
VLI, VUI	V_{LI}, V_{UI}	NXNTD2	R*4	Velocity lower/upper walls
VMEAN	\bar{V}	NXNTD2	R*4	Velocity on mean line
XL, YL	X_L, Y_L	NXNTD2	R*4	Input coordinate lower wall
XU, YU	X_U, Y_U	NXNTD2	R*4	Input coordinate upper wall
XLI, YLI	X_{LI}, Y_{LI}	NXNTD2	R*4	Coordinates lower wall
XUI, YUI	X_{UI}, Y_{UI}	NXNTD2	R*4	Coordinates upper wall

Note: subscript I denotes intersection of approximate potential line
with wall

List of Variables in CØMMØN/CØØRCØ/
Control Options and Parameters

Name	Symbol	Length	Type	Description
DDS	$(\Delta n / \Delta n)_1$		R*4	Ratio uniform/nonuniform grid at wall
IGRID			I*4	Grid option
INUNIT			I*4	Output unit for nonuniform grid
IRUNIT			I*4	Read unit
ISMØØT			I*4	Smoothing option
IUUNIT			I*4	Output unit for uniform grid
IWUNIT			I*4	Print unit
IXFG			I*4	Transfer grid option
JL			I*4	Number of output streamwise stations
JLPTS			I*4	Number of input stations
JXK			I*4	Number of knots for spline
KL			I*4	Number of nonuniform streamlines
KN			I*4	Number uniform streamlines
LØP			I*4	Mesh distortion option
RADR	r_r		R*4	Reference length
TTL	t_L		R*4	Maximum t-plane coordinate lower wall
TTU	t_u		R*4	Maximum t-plane coordinate upper wall

**List of Variables in CØMMØN/CØØRT/
Complex Coordinates and Derivatives**

Name	Symbol	Length	Type	Description
DZDTJ	$\left(\frac{dz}{dt} \right)^J$	KLL	C*16	Mapping derivative
DZDTJP	$\left(\frac{dz}{dt} \right)^{J+1}$	KLL	C*16	Mapping derivative
DZDTP2	$\left(\frac{dz}{dt} \right)^{J+1}$	KLL	C*16	Mapping derivative
DZDT1	$\left(\frac{dz}{dt} \right)^1$	KLL	C*16	Mapping derivative
ZJ	z^J	KLL	C*16	Coordinate in duct plane
ZJP	z^{J+1}	KLL	C*16	Coordinate in duct plane
ZP2	z^{J+2}	KLL	C*16	Coordinate in duct plane
Z1	z^1	KLL	C*16	Coordinate in duct plane

List of Variables in C₀MM₀N/IPDAVS/
Complex Solution Variables

Name	Symbol	Length	Type	Description
B	b ^{v-1}	NXNT	R*8	Location of poles
BNEW	b ^v	NXNT	R*8	Location of new poles
TG	t ^{v-1}	NXNT	C*16	t-plane wall coordinates
TT	t ^v	NXNT	C*16	New t-plane wall coordinates
Z	Z	NXNT	C*16	Z-plane calculated wall coordinates
ZC	Z _c	NXNT	C*16	Z-plane input wall coordinates

List of Variables in CØMMØN/NSDAVS/
Constants and Parameters for Mapping

Name	Symbol	Length	Type	Description
DM	d_m		R*8	Automatic step size in approximate solution
ECØVV	ϵ_c		R*8	Convergence criteria
IC	0. + 1.i		I*4	Complex number $\sqrt{-1}$
ICØRD			I*4	Coordinate generator option
IESTIM			I*4	Approximate potential flow option
IPRINT			I*4	Print option
MAXIT			I*4	Maximum number of iterations
N			I*4	Number of wall points (NLF+2)
NBE			I*4	Number of non-trivial angle changes
NCL, NCU			I*4	Number of lower/upper wall elements
NLF			I*4	Number of lower wall points
NM1			I*4	N-1
NN5			I*4	Number of additional steps in integration
NUI			I*4	NLF+1
NIPØT			I*4	Approximate potential flow option
ØNE	1. + 0.i		C*16	Complex 1.0
XM	M		C*16	Scale constant
ZER	0. + 0i		C*16	Complex 0.0

List of Variables in COMMON/TITLE/
Run Title

Name	Symbol	Length	Type	Description
ITITLE(I)		18	I*4	Run title

List of Variables in CØMMØN/ØPDAVS/

Name	Symbol	Length	Type	Description
ALPHA	α_J	NXNT	R*8	$\operatorname{Re}(\beta_J) + 1.$
BETAM	β_J	NXNT	C*16	Change in wall angle
DELR	$b_{J+1} - b_J$	NXNT	R*8	Difference in pole locations
EXITA	α_E	1	R*8	Duct exit divergence angle + π
HEIGHT	h	1	R*8	Duct inlet height
RATIO	R_J	NXNT	R*8	Ratio of actual to calculated length
THETA1	θ_1	1	R*8	Rotation of duct from real axis
ZET	ζ_J	NXNT	C*16	Estimated pole location

12.0 DETAILED DESCRIPTION OF CDUCT CODE

This section contains an alphabetic list of subroutines and a detailed description of each subroutine. Subroutines that are used by both the ADD code and the CODUCT code are listed and described in Section 7.0. The description of the subroutines which follow have the same format. This format consists of the object or purpose of the subroutine, any options used by the subroutine, and a list of variables not in a COMMON block which are used by the subroutine. Variables in COMMON blocks are listed in Section 6.1 or Section 11.3. Following the list of variables is a brief description of the analysis performed by the subroutine.

12.0 DETAIL DESCRIPTION OF CDUCT CODE

12.1 List of Subroutines

<u>Name</u>	<u>Object</u>
ARCL1	Calculate arc length of input curve
BLKRED	See Section 7.2
CDVDN	Calculate streamline curvature
CØBLK	Block data (IBM version)
CØDUCT	Main program (see Section 11.1)
CLØSUR	Calculate closure error in mapping
CØNSTR	Store fixed data in Q1, Q2 arrays
CØØRD	Calculate coordinates and metrics
CØØRMD	Calculate coordinates J = 2, JL
CØØR1D	Calculate coordinates J = 1
CØRINP	Read coordinate data
CØRSTR	Store coordinates in Q1 array
CRØSS1	See Section 7.2
DERIV3	Calculate 3 point central difference derivative
DRØBRT	See Section 7.2
ESTCØR	Determine location of approximate potential line
ESTIMP	Calculate approximate pole locations
INSECT	Determine intersection of potential line and wall
INTNØR	Calculate end point of potential line
INTSTR	Calculate end point of streamline

12.1 List of Subroutines (Cont'd)

<u>Name</u>	<u>Object</u>
KURVTR	Calculate curvature of input curve
MDAVIS	Solve Schwartz-Christoffel mapping
NØRLIN	Calculate single potential line
QPKURV	Interpolates curvatures at output location
QPSTØR	Store Q parameters in Q1, Q2 arrays
Q2INTP	Interpolate from uniform to non-uniform mesh
RCNTRL	Reads user input control parameters
RØTATM	Calculate duct rotation and scaling
SMARCL	Cubic spline smoothing on arc length
SMØØTH	See Section 7.2
STEP	Davis' integration formula
STRSTP	Integrate each streamline one step
SUNBAR	Store X, Y data into interpolation table T
TTUP	Update upper wall upstream point
UNBAR	Lagrange table interpolation
WALLV	Approximate potential flow wall velocity
XFGRID	Interpolate uniform to nonuniform grid

12.2 Description of Subroutines

Subroutine ARCL1 (X,Y,NPT,S)

Object

Calculate arc length of input curve

Options

None

Symbols

NPT		Number of input points
S(I)	S_I	Arc length
X(I),Y(I)	X_I, Y_I	Coordinates of input curve

Theory

The arc length of a curve is given by

$$S_J = \sum_{I=2}^J \left\{ (X_I - X_{I-1})^2 + (Y_I - Y_{I-1})^2 \right\}^{1/2} \quad (1)$$

Subroutine CDVDN (NPT,DZDT)

Object

Calculate streamline curvature

Options

None

List of Symbols

DZDT	dZ/dt	,	Complex derivative of mapping
NPT		,	Number of points in DZDT
Q1(7,K) $\partial v / \partial n$,		Streamline curvature

Theory

The magnitude of the potential flow velocity is

$$V = \left| \frac{dt}{dz} \right| \quad (1)$$

Then the streamline curvature is given by

$$\kappa = -\partial V / \partial n \quad (2)$$

The curvature is obtained by numerical differentiation using subroutine DERIV3 for K = 2, KL = 1. At the wall the streamline curvature is given by the wall curvature obtained from the input data.

Subroutine CLØSUR

Object

Calculate closure error in mapping

Options

None

List of Symbols

NLF		Number of wall points
Z	Z	Duct plane coordinates
ZCL	ϵ_{CL}	Closure error
TT	t	t-plane coordinates

Theory

The solution is integrated from t_1 to $t_{NLF} + i$ by two paths to close the polygon. The closure error is defined by

$$\epsilon_{CL} = |Z(t_{NLF} + i)_1 - Z(t_{NLF} + i)_2| \quad (1)$$

Subroutine CBLK

BLOCK DATA

Object

Defines default values for program control

List of Symbols

NXNT	Maximum number of wall definition points total
NXNTD2	Maximum number of wall definition points for each wall, also maximum number of potential lines permissible
IST	Maximum number of streamlines
NVK	Maximum number of knots to use in cubic-spline fit to wall data
IPOINT	Logical unit number to read from
IWUNIT	Logical unit number to write to

Subroutine C \emptyset NSTR

Object

Store fixed data in Q1, Q2 arrays

Options

IGRID = 0	Uniform mesh
= 1	Nonuniform mesh
= 2	Both meshes

Input Symbols

DDS	$(\Delta\eta/\Delta n)_1$	Mesh distortion parameter
DETA	$\Delta\eta$	Uniform transverse step size
JL		Number of streamwise stations
KL		Number of nonuniform streamlines
KN		Number of uniform streamlines
L \emptyset P		Mesh distortion option
SAVG		Average length of duct

Output Symbols

Q1	Uniform mesh block data
Q2	Nonuniform mesh block data

Theory

C \emptyset NSTR is a general setup program that stores information into the Q1 and Q2 data blocks. These stored variables are ones that do not change for J = 1, JL.

$$\left. \begin{array}{l} Q1(5,K) = 1. \\ Q1(16,K) = 0. \\ Q1(17,K) = 0. \\ Q1(18,K) = \eta \end{array} \right\} \quad K = 1, KN \quad (1)$$

$$\left. \begin{array}{l} Q2(5,K) = 1. \\ Q2(16,K) = d\eta/dn \\ Q2(17,K) = n \\ Q2(18,K) = \eta \end{array} \right\} \quad (2)$$

Subroutine C ϕ RD

Object

Calculate coordinates and metrics

Options

IGRID = 0	Uniform grid output to IUUNIT
= 1	Nonuniform grid output to INUNIT
= 2	Output both grids

Input Signals

DDS	$\Delta\eta/\Delta n$	Mesh distortion parameter
DETA	$\Delta\eta$	Uniform step size
JL		Number of streamwise stations
JLPTS		Number of points on wall
KL		Number of nonuniform streamlines
KN		Number of uniform streamlines
L ϕ P		Mesh distortion option
NNS		Number of steps on potential line

Output Symbols

Q1(I,K)	Coordinate data uniform grid
Q2(I,K)	Coordinate data nonuniform grid

Theory

Once the mapping solution has converged, the location of the poles are known and the solution can be obtained for any interior point by integrating the Schwartz-Christoffel transformation. The streamwise integration step ΔS is defined in subroutine C ϕ NSTR by

$$\Delta S = (\max(t_U, t_L) - \min(t_U, t_L)) / (JL - 1) \quad (1)$$

and the normal integration step is defined by

$$\Delta n = 1 / (KN - 1) \quad (2)$$

Then integration of dZ/dt with n constant produces a streamline and integration with S constant produces a potential line.

Subroutine CØØRD (Cont'd)

To start the coordinate calculation, CØØR1D is called to integrate the first potential line at the duct inlet. We note that dz/dt calculated by subroutine STEP is evaluated at the point

$$n_{k+1/2} = (n_{k+1} + n_k) / 2 \quad (3)$$

such that the metric is given by

$$\left(\frac{dz}{dt}\right)_k = \frac{1}{2} \left[\left(\frac{dz}{dt}\right)_{k+1/2} + \left(\frac{dz}{dt}\right)_{k-1/2} \right] \quad (4)$$

$$v_k = 1 / \left| \frac{dz}{dt} \right|_k \quad (5)$$

The remainder of the computation grid is constructed by integrating all the streamlines in the streamwise direction one step using subroutine CØØRMD. Again we note that the derivative is evaluated at the mid point so that

$$\left(\frac{dz}{dt}\right)^j = \frac{1}{2} \left[\left(\frac{dz}{dt}\right)^{j+1/2} - \left(\frac{dz}{dt}\right)^{j-1/2} \right] \quad (6)$$

$$v^j = 1 / \left| \frac{dz}{dt} \right|^j \quad (7)$$

The integration is continued to $J = JL + 1/2$.

Subroutine CORMD (J)

Object

Calculate coordinates J = 2, JL

Options

IGRID = 0	Uniform grid output to IUUNIT
= 1	Nonuniform grid output to INUNIT
= 2	Output both grids

Input Symbols

DSTEP	ΔS	Streamwise step size
DZDTJ	$\left(\frac{dZ}{dt}\right)^J$	Derivative at J
DZDTJ1	$\left(\frac{dZ}{dt}\right)^{J-1}$	Derivative at J-1
J		Streamwise index
KL		Number of nonuniform streamlines
KN		Number of uniform streamlines
ZJ	Z^J	Coordinate at J
ZJ1	Z^{J-1}	Coordinate at J-1

Output Symbols

Q1	Coordinate data uniform grid
Q2	Coordinate data nonuniform grid

Theory

The derivatives of the metrics ($\partial V / \partial n$, $\partial V / \partial S$) are obtained by the three point difference formula. Thus we have

$$\left(\frac{dZ}{dt}\right)_K^J = \frac{1}{2} \left[\left(\frac{dZ}{dt}\right)_K^{J+1/2} + \left(\frac{dZ}{dt}\right)_K^{J-1/2} \right] \quad (1)$$

and

$$V_K^J = 1 / \left| \frac{dZ}{dt} \right|_K^J \quad (2)$$

Subroutine CØRMD (Cont'd)

Since dZ/dt are known at the mid points we have

$$\frac{dV_K^J}{ds} = \frac{1}{2\Delta s} \left\{ \frac{1}{2} [V_K^{J+1/2} + V_K^{J+3/2}] - V_K^{J-1} \right\} \quad (3)$$

The derivative $\partial V / \partial n$ is obtained using subroutine CDVDN and the remaining variables are defined and calculated for the KN points on the uniform mesh by calling subroutine CØRSTR. Subroutine Q2INTP interpolates from the KN uniform mesh points to the KL nonuniform mesh points.

Subroutine CØØR1D

Object

Calculate coordinates at J = 1

Options

IGRID = 0 Uniform grid output to IUUNIT
 = 1 Nonuniform grid output to INUNIT
 = 2 Output both grids

Input Symbols

DSTEP	ΔS	Streamwise step size
KL		Number of nonuniform streamlines
KN		Number of uniform streamlines
NNS		Number of steps in n integration

Output Symbols

DZDT2	Derivative at J = 2
DZDT3	Derivative at J = 1
Q1	Coordinate data for uniform grid
Q2	Coordinate data for nonuniform grid
Z2	Coordinate at J = 2
Z3	Coordinate at J = 3

Theory

The first potential line is calculated by calling subroutine NØRLIN. Then derivatives of the metrics ($\partial V / \partial n$, $\partial V / \partial S$) are obtained by 3 point difference formula. Thus we have

$$\left(\frac{dZ}{dt} \right)_K^J = \frac{1}{2} \left[\left(\frac{dZ}{dt} \right)_K^{J+1/2} + \left(\frac{dZ}{dt} \right)_K^{J-1/2} \right] \quad (1)$$

$$V_K^J = 1 / \left| \frac{dZ}{dt} \right|_K^J \quad (2)$$

The streamlines are integrated to J = 4 using subroutine STRSTP. Then we have

$$\left(\frac{\partial V}{\partial S} \right)_K^I = \frac{1}{\Delta S} \left\{ -3V_K^I + 4 \left[\frac{V_K^{3/2} + V_K^{5/2}}{2} \right] - \left[V_K^{5/2} + V_K^{7/2} \right] \right\} \quad (3)$$

Subroutine CØR1D (Cont'd)

The derivative $\partial V / \partial n$ is calculated using subroutine CDVDN and the remaining variables are defined and calculated for the KN points on the uniform grid by calling subroutine CØRSTR. Subroutine Q2INTP interpolates from the KN uniform grid to the KL nonuniform grid.

Subroutine CØRINP

Object

Read coordinate data

Options

ISMØØT	= 0	Do not smooth wall data
	= 1	Smooth wall data

Input Symbols

JLPTS	Number of smoothed wall data points
JXK	Number of knots in spline smoothing
NLF	Number of input upper/lower wall data points

Output Symbols

XL,YL	X _L ,Y _L	Lower wall data points
XU,YU	X _U ,Y _U	Upper wall data points
ZC	X _C	Complex coordinates of wall data points
RADR	r _r	Reference radius XU(1)

Theory

The subroutine reads the wall data in card image form. If ISMØØT = 1, a cubic spline smoothing routine SMARCL will produce a set of JLPTS data points for each wall. This subroutine also prints the smoothed and unsmoothed wall data.

Subroutine CØRSTR (J,ZI,DZDT)

Object

Store coordinates in Q1 array

Options

None

Input Symbols

J	Streamwise station number	
DZDT	$\left(\frac{dZ}{dt}\right)^J$	Derivative at J
ZI	Z^J	Coordinates at J

Output Symbols

Q1	Coordinate data block
----	-----------------------

Theory

The following coordinate data are calculated at J.

$$Q1(1,K) = \operatorname{Im} (Z_K^J) = R \quad (1)$$

$$Q1(2,K) = \operatorname{Re} (Z_K^J) = Z \quad (2)$$

$$Q1(3,K) = \operatorname{Re} (dZ/dt)_K^J = \partial R / \partial n \quad (3)$$

$$Q1(4,K) = \operatorname{Im} (dZ/dt)_K^J = \partial R / \partial S \quad (4)$$

$$Q1(6,K) = 1 / |dZ/dt|_K^J = V \quad (5)$$

$$Q1(9,K) = \int_o^{S_J} \frac{ds}{V} = X \quad (6)$$

$$Q1(10,K) = \int_o^n \frac{dn}{V} = Y \quad (7)$$

$$Q1(11,K) = Q1(10,K) / Q1(10,KN) \quad (8)$$

$$Q1(12,K) = 2\pi \int_o^n \frac{Rdn}{V} = A \quad (10)$$

$$Q1(13,K) = 2\pi R \quad (11)$$

$$Q1(14,K) = 2\pi \partial R / \partial n \quad (12)$$

$$Q1(15,K) = 2\pi \partial R / \partial S \quad (13)$$

Subroutine DERIV3 (X,Y,NX,NPT,DYDX,D2YDX2)

Object

Calculate 3 point central difference derivative

Options

None

Input Symbols

NPT	Point at which to evaluate derivative
NX	Number of data points for X and Y
X,Y	Table of NX independent/dependent variables

Output Symbols

DYDX	$\frac{dy}{dx}$	First derivative
D2YDX2	$\frac{d^2y}{dx^2}$	Second derivative

Theory

The finite difference formula are given by:

$$\left(\frac{dy}{dx}\right)^I = \frac{Y^{I+1} - (1-r^2)Y^I - r^2Y^{I-1}}{X^{I+1} - X^I + r^2(X^I - X^{I-1})} \quad (1)$$

$$\left(\frac{d^2y}{dx^2}\right)^I = \frac{Y^{I+1} - (1+r)Y^I + rY^{I-1}}{(X^{I+1} - X^I)^2 + r(X^I - X^{I-1})^2} \quad (2)$$

$$r = \frac{X^{I+1} - X^I}{X^I - X^{I-1}} \quad (3)$$

If I = 1 or NPT a diagnostic is printed

"INPUT POINT XX OUT OF RANGE"

and both derivatives are set to 1.0.

Subroutine DERIV3 (X,Y,NX,NPT,DYDX,D2YDX2) (Cont'd)

If $|x^{I+1} - x^I|$ or $|x^I - x^{I-1}| < 10^{-15}$ a diagnostic is printed

"INDEPENDENT VARIABLE STEP SIZE LT 1.E-15"

and both derivatives are set to 1.0.

Subroutine ESTC θ R (SAVG, NPOT)

Object

Determine location of approximate potential line.

Option

NIP θ T	=	0	Program determines number of lines
	>	1	NIP θ T lines are calculated

Input Symbols

NP θ T	N_p	Number of potential lines
SAVG	\bar{S}	Average duct length
XL,YL	X_L, Y_L	Lower wall coordinates
XU,YU	X_U, Y_U	Upper wall coordinates

Output Symbols

HT	h	Height of duct
IU,IL		
TH	θ	Angle of mean line
XLI,YLI	X_{LI}, Y_{LI}	Coordinates potential line lower wall
XUI,YUI	X_{UI}, Y_{UI}	Coordinates potential line upper wall

Theory

The object is to determine NP θ T approximate potential lines in the duct where NP θ T = NLF/3 initially. The first potential line intersects the duct at Z_{U1} and Z_{L1} where the complex notation is used.

$$Z = X + iY \quad (1)$$

Subroutine ESTCØR (Cont'd)

We then construct a mean line Z_m , (See Fig. 1), which satisfies the following conditions:

$$|Z_{m,j} - Z_{m,j-1}| = \Delta s \quad (2)$$

$$|Z_{UI,j} - Z_{m,j}| = |Z_{m,j} - Z_{LI,j}| \quad (3)$$

$$(Z_{UI,j} - Z_{LI,j}) \cdot (Z_{m,j} - Z_{m,j-1}) = 0 \quad (4)$$

It was found that the set of equations, Eq. (2) through (4) do not have a unique solution. Therefore Eq. (3) was replaced by a minimum condition on D where:

$$D = 1 - \frac{|Z_{UI,j} - Z_{m,j}|}{|Z_{m,j} - Z_{LI,j}|} \quad (5)$$

The algorithm consists of finding an angle θ_j^ν which minimizes D. Thus we have from Eq. (1),

$$Z_{m,j}^\nu = Z_{m,j-1} + \Delta s \cdot [\cos \theta_j^\nu + i \sin \theta_j^\nu] \quad (6)$$

A straight line normal to the mean line, from Eq. (4), is defined by the point $Z_{m,j}^\nu$ and the point,

$$\tilde{Z} = Z_{m,j} + \Delta s \cdot [\cos (\theta_j^\nu + \pi/2) + i \sin (\theta_j^\nu + \pi/2)] \quad (7)$$

The intersections of the line $(Z, Z_{m,j}^\nu)$ with the duct wall $(Z_{UI,j}^\nu, Z_{LI,j}^\nu)$ is determined using subroutine INSECT. Then D is calculated and checked for a minimum. An iteration procedure determines the θ_j^ν which minimizes D.

Subroutine ESTCOR (Cont'd)

When the iteration has converged, a check is made to determine if the $Z_{m,J}$ potential line crosses the $Z_{m,J-1}$ potential line inside the duct. If it does, the distance along the mean line ΔS is increased

$$\Delta S = \Delta S \cdot 1.2 \quad (8)$$

and the algorithm is repeated starting with Eq. (6). A maximum step ΔS is fixed by some fraction of the duct height d_m . Thus

$$\Delta S = \min [d_m |Z_{UI,J} - Z_{LI,J}|, \Delta S] \quad (9)$$

$$Z = X + iY$$

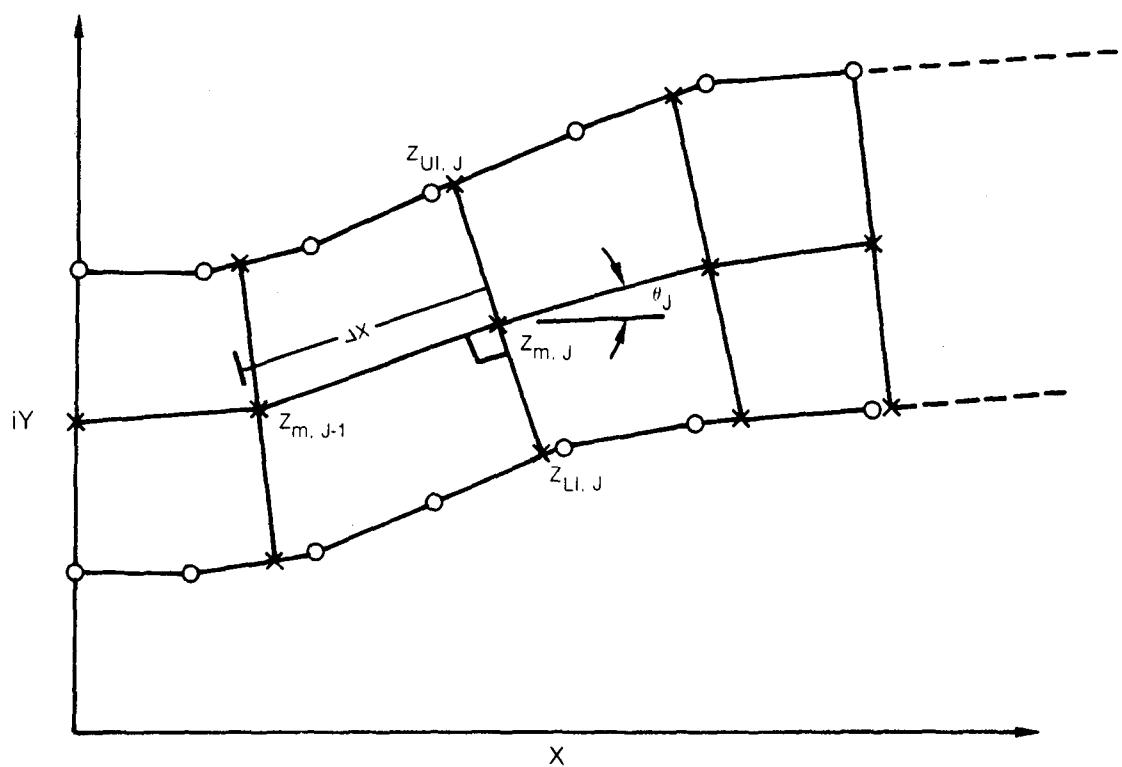


Fig. 1. Geometric Construction of Potential Flow

Subroutine ESTIMP

Object

Calculate approximate pole locations

Options

None

Input Symbols

N	Total number of poles (2*NLF)
NLF	Number of poles on each wall
ZC	Duct coordinates

Output Symbols

B	b_I	Pole locations in plane
TT	t_I	Pole locations in t plane

Theory

The arc lengths S_U, S_L to each pole in the duct (Z) plane is determined using subroutine ARCL1. Subroutine ESTC0R calculates the location of the approximate potential line and subroutine WALLV calculates the approximate potential flow velocities (metrics) at the pole locations in the Z plane. Then the pole locations are given by:

$$t_{U_I} = \int_0^{S_{U_I}} v_{U_I} ds \quad (1)$$

$$t_{L_I} = \int_0^{S_{L_I}} v_{L_I} ds \quad (2)$$

$$b_{U_I} = \exp(-\pi t_{U_I}) \quad (3)$$

$$b_{L_I} = -\exp(-\pi t_{L_I}) \quad (4)$$

Subroutine INSECT (Arg. List)

Object

Determine determine intersection of potential line and wall.

Options

IEXTNP = 1	Extend last line segment for intersection
# 1	Do not extend last line segment.

Argument List

(X1,Y1),(X2,Y2)	Points defining potential line	
X,Y	Z	Points defining wall curve
NPT	Number of (X,Y) points	
(XI,YI)	Z _I	Intersection point
IØ	Lower index of intersection point	
IERR	Error flag = 0 intersection found = -1 no intersection found	

Theory

The input coordinates (X,Y) are searched for an intersection with (X1,Y1), (X2,Y2) using subroutine CROSS1 which determines if an intersection occurs between

$$Z(I\emptyset) \leq Z_I \leq Z(I\emptyset + 1) \quad (1)$$

Subroutine INTNØR (Arg. List)

Object

Calculate end point of potential line

Options

None

Argument List

ZETO	ζ_0	Starting location in ζ plane
Z0	Z_0	Starting location in Z plane
ZETU	ζ_u	Final location in ζ plane
ZU	Z_u	Final location in Z plane
NNNS	Number of steps	

Theory

The starting location in the t plane is given by

$$t_0 = i - \ln(\zeta_0) / \Pi \quad (1)$$

and the step size is given by

$$\Delta t = i \cdot 1. / (NNNS - 1) \quad (2)$$

Then

$$Z_u = Z_0 + \sum_{j=1}^{NNNS-1} \left\{ \int_{t_0 + \Delta t(j-1)}^{t_0 + \Delta t \cdot j} \frac{dZ}{dt} dt \right\} \quad (3)$$

where the term in the bracket is evaluated using subroutine STEP.

Subroutine INTSTR (Arg. List)

Object

Calculate end point of streamline

Options

None

Argument List

ZETO	ζ_0	Starting location in ζ plane
Z0	z_0	Starting location in Z plane
ZETU	ζ_U	Final location in ζ plane
ZU	z_U	Final location in Z plane

List of Symbols

NLF		Number of lower wall points
TT	t_I	Pole locations in t plane

Theory

The starting point in the t plane is given by

$$t_0 = i - \ln(\zeta_0) / \pi \quad (1)$$

Define the streamline by

$$t_n = \operatorname{Im}(t_0) \quad (2)$$

Then

$$z_U = z_0 + \sum_{I=2}^{NLF} \left\{ \int_{t_{I-1} + t_n \cdot i}^{t_{I-1} + t_n \cdot i} \frac{dz}{dt} dt \right\} \quad (3)$$

where the bracket is evaluated using subroutine STEP.

Subroutine KURVTR (Arg. List)

Object

Calculate curvature of input curve

Options

None

Argument List

X,Y	X,Y	Coordinates of input curve
S	S	Arc length of input curve
NPT		Number of points on curve
KURV	κ	Curvature of input curve

Theory

The principal curvature of a curve is given by

$$\kappa = \frac{dx}{ds} \frac{d^2y}{ds^2} - \frac{dy}{ds} \frac{d^2x}{ds^2} \quad (1)$$

Eq. (1) is evaluated by 3 point finite difference formula

Subroutine MDAVIS

Object

Solve Schwartz-Christoffel Mapping

Options

None

Input Symbols

EC \emptyset N	ϵ_c	Convergence criteria
NLF		Number of points on wall
TT	t	Initial pole location t plane
ZC	z_c	Duct wall coordinates

Output Symbols

TT	t	Final pole location in t plane
Z	z	Final pole location in Z plane

Theory

The flow chart for this subroutine is shown on Fig. 2 and takes place in the following steps:

Step_1_Initialization

- a) Calculate rotation constant M
- b) Calculate duct exit divergence angle α_e
- c) Calculate Schwartz-Christoffel pole angle α_i

Step_2_Integrate_Transformation

- a) Integrate Schwartz-Christoffel transformation along each wall with a guess for the b_i 's in the ζ plane using subroutine STEP.
- b) Integrate Schwartz-Christoffel transformation along far upstream potential line with a guess for b_i 's in ζ plane using subroutine NØRLIN.

Subroutine MDAVIS (Cont'd)

Step_3_Update_Poles

- a) Update poles on lower wall in t plane by ratio of arc lengths.
- b) Update first pole on upper wall using Step 2b.
- c) Update poles on upper wall in t plane by ratio of arc lengths.
- d) Calculate pole location b_i 's in ζ plane.

Step_4_Check_Convergence

- a) Calculate absolute error for all poles

$$\epsilon_i = |z_i - z_{Ci}|$$

- b) Check convergence

$$\max(\epsilon_i) < \epsilon_c$$

- c) Calculate closure error using subroutine CLØSUR
- d) If not converged repeat Steps 2, 3, 4
If converged return

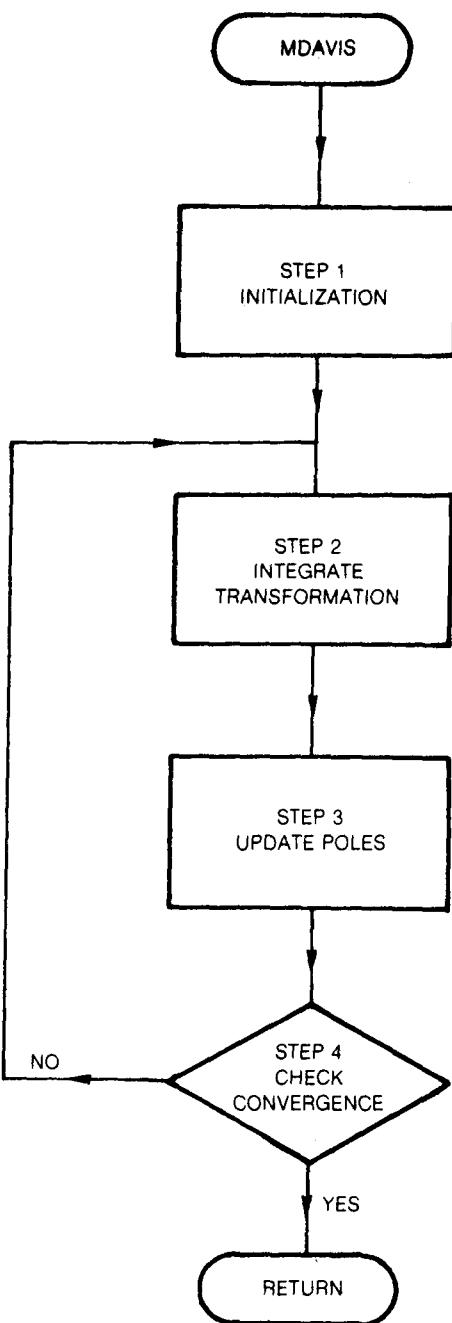


Fig. 2. Flow Chart for Subsonic MDAVIS

Subroutine NØRLIN (J,Z)

Object

Calculate single potential line

Options

None

Input Symbols

J		Calculate Jth potential line
KN		Number of output stations
NNS		Number of integration steps
TT	t_i	Pole locations in t plane
Z0	Z_0	Initial Z location

Output Symbols

Z1	Z_K	Coordinates of potential line
DZDT1	$(dZ/dt)_K$	Derivative

Theory

After a converged solution for the pole locations is obtained, this subroutine integrates the potential line at the Jth station in NNS steps and outputs the coordinates and derivatives of KN stations. Then let us choose

$$NNS = NSD * (KN - 1) + KN \quad (1)$$

where NSD is the number of integration steps per output station. The integration starts at Z_0 in the Z plane and t_0 given by

$$t_0 = DSTEP (J - 1) - t_L / 2 + 0 + i \quad (2)$$

in the t plane. The parameter t_L is chosen in the approximate coordinate calculation to center the pole distributions about plus and minus values.

Subroutine NØRLIN (Cont'd)

The integration step is then given by

$$\Delta t = 1 / (NNS - 1) * i \quad (3)$$

Then we have the recursion formula

$$Z_i = Z_0 \quad (4)$$

$$Z_k = Z_{k-1} + \int_{t_{k-1} + \Delta t \cdot (L-1)}^{t_{k-1} + \Delta t \cdot L} \frac{dZ}{dt} dt \quad (5)$$

$$\left(\frac{dZ}{dt} \right)_{t_k} = \frac{1}{2} \left[\left(\frac{dZ}{dt} \right)_{t_{k-1}} + \left(\frac{dZ}{dt} \right)_{t_k + \Delta t} \right] \quad (6)$$

Subroutine QPKURV

Object

Interpolates wall curvature at output location

Options

None

Input Symbols

KKL,KKU	K_L, K_U	Curvature of lower/upper wall
XL,YL	X_L, Y_L	Input coordinates lower wall
XU,YU	X_U, Y_U	Input coordinates upper wall
SL,SU	S_L, S_U	Arc length lower/upper wall
Q1		Coordinate data

Output Symbols

RHS1(3)	$K_L(J)$	Curvature lower wall
RTS1(3)	$K_U(J)$	Curvature upper wall

Theory

The streamline curvature KKL and KKU is known at the input data points (XL,YL) and (XU,YU) respectively. The coordinates are known at station J for equal streamwise steps DSTEP. Let (X_L, Y_L) and (X_U, Y_U) be the lower and upper wall coordinates at station J obtained from the Q1 array. A straight line is passed through these points and a search of the input coordinates is made using subroutine INSECT to determine the intersection on each wall. Subroutine INSECT returns an interpolation parameter which is used to calculate $K_L(J), K_U(J)$

Subroutine QPSTOR(J)

Object

Store Q parameters in Q1, Q2 arrays

Options

IGRID	=	0	Uniform grid
	=	1	Nonuniform grid
	=	2	Both grids
IXFG	=	0	Uniform grid
	=	1	Interpolate only

Input Symbols

DSTEP	ΔS	Streamwise step size
JL		Number of potential lines
KL		Number of streamlines
RADR	r_r	Reference radius

Output Symbols

RHS1, RMS1, RTS1	Wall coordinate data uniform grid
RHS2, RMS2, RTS2	Wall coordinate data nonuniform grid
QPARM1	Parameters for uniform grid
QPARM2	Parameters for nonuniform grid

Theory

The wall coordinate data and grid parameters are calculated by this subroutine.

Subroutine Q2INTP

Object

Interpolate from uniform grid to nonuniform grid

Options

None

Input Sybmols

KL	Number of output streamlines
KN	Number of input streamlines
Q1	Coordinate data for uniform grid

Output Symbols

Q2	Coordinate data for nonuniform grid
----	-------------------------------------

Theory

The normal coordinate for a uniform grid is Q1(19,K) K=1,KN and the normal coordinate for the nonuniform grid is Q2(18,K) K=1,KL. The Q2 variables are obtained from the Q1 variables by linear interpolation using the normal coordinate as the independent variable.

Subroutine RCNTRL

Object

Reads user input control parameters

Options

None

Input Signals

See input data Section 10.2

Theory

This subroutine reads the input control parameters, checks for inconsistencies and prints the input data.

Subroutine ROTATM

Object

Calculate duct rotation and scaling

Options

None

Input Symbols

ZC Z_C Input duct coordinates

Output Symbols

XM M Rotational constant

Theory

Far upstream of the duct inlet $\zeta \rightarrow \infty$ and the Schwartz-Christoffel transformation reduces to

$$\frac{dz}{d\zeta} = \frac{M}{\zeta} \quad (1)$$

Integrating Eq. (1) we have

$$z = M \ln \zeta + z_0 \quad (2)$$

The transformation to the t plane is given by

$$\ln \zeta = \pi (i - t) \quad (3)$$

and Eq. (2) becomes a duct with parallel walls.

$$z = M \pi (i - t) + z_0 \quad (4)$$

Subtracting the lower wall from the upper wall we have

$$z_u - z_l = - M \pi i \quad (5)$$

Subroutine ROTATM (Cont'd)

The height of the duct is given by

$$H = |Z_U - Z_L| \quad (6)$$

Hence

$$Z_U - Z_L = H e^{i(\theta + \pi/2)} \quad (7)$$

where θ is the angle of the duct with respect to the real axis.

Then solving for M using Eq. (5) and Eq. (7) we have

$$M = \frac{-H}{\pi} e^{i\theta} \quad (8)$$

Since this solution requires parallel walls, this subroutine will modify the Nth point of the data set to insure parallel walls at the inlet so that the correct duct height H can be determined at the inlet.

Subroutine SMARCL (Arg. List)

Object

Cubic spline smoothing on arc length

Options

None

Argument List

JX		Number of input coordinate points
JXB		Number of ouptut coordinate points
JXK		Number of knots in spline fit
X,Y	X,Y	Input coordinates
S	X	Arc length along input curve
SB	\bar{S}	Arc length along output curve
XB,YB	\bar{X}, \bar{Y}	Output smoothed coordinates

Theory

The arc length along the input curve is calculated using subroutine ARCL1. Then an increment of arc length is defined by

$$\Delta \bar{S} = (S(JX) - S(I)) / (JXB - I) \quad (1)$$

The curves X(S) and Y(S) are smoothed using subroutine SMOTH which returns $\bar{X}(S)$ and $\bar{Y}(S)$ for JXB points spaced ΔS in length

Subroutine STEP(ZETD1,DZETD,DZ)

Object

Calculate Integration Step For Schwartz-Christoffel Transformation

Options

None

Variables

B(K)	=	b _K	,	Location of pole in ζ plane
BETM(K)	=	- α_K/π	,	Turning angle in Z plane
DZ	=	ΔZ_m	,	Step size in Z plane
DZETD	=	$\Delta \zeta_m$,	Step size in ζ plane
		Δt_m	,	Step size in t plane
XM	=	M	,	Scale factor
ZETD1	=	ζ_m	,	Initial ζ
ZETD2	=	ζ_{m+1}	,	Final ζ
NBE	=	N	,	Number of poles
GAMA	=	γ_m	,	Exit divergence angle

Theory

The second order integration formula evaluated at the mid point is given by Davis Ref. 1 as

$$\left(\frac{dz}{d\zeta}\right)_{M+1/2} = \frac{M}{\zeta_{M+1/2}} \zeta_{M+1/2}^{\alpha M/\pi} \sum_{I=1}^N \frac{\left(\zeta_{M+1} - b_I\right)^{-\alpha_I/\pi + 1} - (\zeta_M - b_I)^{-\alpha_I/\pi + 1}}{\Delta \zeta_M (-\alpha_I/\pi + 1)} \quad (1)$$

where

$$\Delta \zeta_M = \zeta_{M+1} - \zeta_M \quad (2)$$

$$\zeta_{M+1/2} = \frac{1}{2} (\zeta_{M+1} + \zeta_M) \quad (3)$$

Subroutine STEP (Cont'd)

The transformation to the t plane is given by

$$\left(\frac{dt}{d\zeta}\right)_{M+1/2} = -\frac{1}{\pi \zeta_{M+1/2}} \quad (4)$$

Then we have

$$\Delta z_M = \left(\frac{dz}{d\zeta}\right)_{M+1/2} / \left(\frac{dt}{d\zeta}\right)_{M+1/2} \Delta t_M \quad (5)$$

where Δt_M is chosen by the input ζ 's.

$$\Delta t = -(\ln \zeta_{M+1} - \ln \zeta_M) / \pi \quad (6)$$

References

1. Davis, R. T.: Numerical Methods for Coordinate Generation Based on Schwartz-Christoffel Transformations.

Subroutine STRSTP

Object

Integrate each streamline one step

Options

None

Argument List

J		Streamwise station
ZI	Z^J	Coordinates at J
Z0	Z^{J+1}	Coordinates at J+1
DZDTO	$(dZ/dt)^{J+1/2}$	Derivative at mid point

Theory

This subroutine integrates K = 1, KN streamlines one step

$$Z_K^{J+1} = Z_K^J + \left(\frac{dZ}{dt} \right)_K^{J+1/2} \Delta t \quad (1)$$

using subroutine STEP.

Subroutine SUNBAR (X,Y,T,NPT,NORDER)

Object

Stores X,Y data into interpolating Table T

Options

None

Input Symbols

X,Y	x,y	Independent variable arrays
NPT		Number of data pairs (X,Y)
NORDER		Interpolation order (= 1, 2 or 3)

Output Symbols

T	Output interpolation table
---	----------------------------

Theory

The data is stored into T as follows

T(1) = 1.
T(2) = NORDER
T(3) = NPT
T(4) = 0.
T(J + 4) = X(J), J = 1,NPT
T(J + NPT + 4) = Y(J), J = 1,NPT

Subroutine TTUP (ITER,ZU)

Object

Update upper wall upstream point

Options

None

Input Symbols

ITER	v	Iteration number
THETAL	θ_1	Angle of duct rotation from real axis
TT	t_i^v	Location of poles in t plane
ZC	z_{ci}	Input wall coordinates
ZU	z_U	End point of potential line integration

Output Symbols

TT(N)	t_N^{v+1}	Updated t plane coordinate at point N
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Theory

This subroutine updates the corner point z_N to close the polygon by jumping from the lower wall to the upper wall as shown in Fig. 3. With known t_i^v , the point z_N^v is determined by integrating along the path (z_{cl}, A, z_N^v) . The error in closing the polygon is given by

$$\epsilon = |z_N^v - z_{CN}| \quad (1)$$

The update t_N^{v+1} is determined in the following manner. Let us define upstream points t_1' and t_N' given by

$$t_1' = t_1 - \sigma |t_1^v| \quad (2)$$

$$t_N' = f_1 + i \quad (3)$$

Subroutine TTUP (Cont'd)

where σ is a parameter chosen to move t_1' sufficiently upstream to approximate the limiting case $t \rightarrow -\infty$

$$Z = \pi M (i - t) + Z_0 \quad (4)$$

Then

$$Z_N' - Z_1' = -\pi M i \quad (5)$$

The point Z_1' is determined by integrating along the path (Z_{c1}, Z_i') and Z_N' is determined from Eq. (5). A ratio of wall lengths is defined

$$R = \frac{|Z_{CN} - Z_N'|}{|Z_N^v - Z_N'|} \quad (6)$$

and the update for t_N^v is given by

$$t_N^{v+1} = t_N' + R (t_N^v - t_N') \quad (7)$$

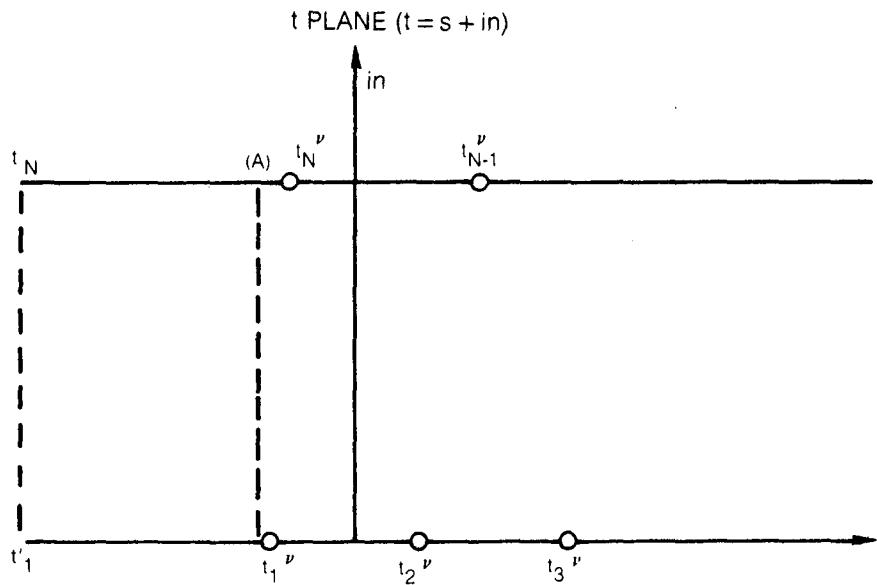
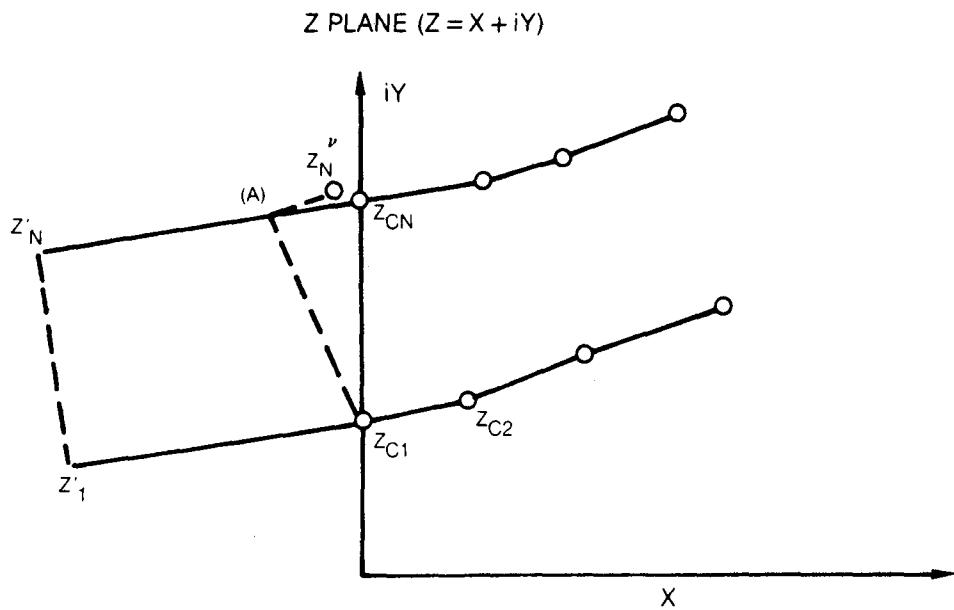


Fig. 3. Update for Corner Point

Subroutine UNBAR (T,IK,XIN,YIN,ZZ,KK)

Object

Interpolate a univariate or bivariate table.

Input Symbols

T	=	Name of the array which contains the table values.
IK	=	Element of the array at which the table starts. If you have only one table in the array, IK=ONE.
XIN	=	Independent variable in the X-sense.
YIN	=	Independent variable in the Y-sense. If the table is a univariate, then YIN is zero.

Output Symbols

ZZ	=	Dependent variable
KK	=	Off Table indicator
	=	0 Normal evaluation
	=	1 Off On X Min.
	=	2 Off On X Max.
	=	3 Off On Y Min.
	=	4 Off On X Min. and Y Min.
	=	5 Off On X Max. and Y Min.
	=	6 Off On Y Max.
	=	7 Off On X Min. and Y Max.
	=	8 Off On X Max. and Y Max.
	=	Less Than 0, Table set up wrong.

Theory

If either variable is off the table, UNBAR will return the corner value.. This implies that UNBAR will not extrapolate and does not recognize any discontinuities. The table must be set up as follows-all numbers are in floating point mode.

T(IK) =	Curve No.
T(IK+1) =	Degree of Interpolating (1, 2, 3)
T(IK+2) =	NX. No. of X values
T(IK+3) =	NY. No. of Y values. (in univariate make zero)
T(IK++) =	X values in ascending order.
T(IK++) =	Y values in ascending order.
T(IK++) =	Z values. Put them in following order- (Z(1,1),Z(1,2), Z(1,3)---Z(1,NY),Z(2,1),Z(2,2)---Z(2,NY)---Z(NX,1), Z(NX,2)---Z(NX,NY). For bivariate only.

Subroutine UNBAR (Cont'd)

A Lagrangian interpolation polynomial of degree 1, 2 or 3 will be used for the interpolation depending upon T(IK+l).

Subroutine WALLV

Object

Approximate potential flow velocity

Options

None

Input Symbols

HT	h	,	Approximate duct height
IL,IU		,	Indices for lower/upper wall potential line
NPOT	N _P	,	Number of potential lines
SAVG	\bar{s}	,	Average duct length
SL,SU	S _L ,S _U	,	Arc length lower/upper wall
TH	θ	,	Mean line angle
XL,YL	X _L ,Y _L	,	Coordinates lower wall
XU,YU	X _U ,Y _U	,	Coordinates upper wall
XLI,YLI	X _{LI} ,Y _{LI}	,	ESTCØR coordinates lower wall
XUI,YUI	X _{UI} ,Y _{UI}	,	ESTCØR coordinates upper wall

Output Symbols

VL,VU	V _L ,V _U	,	Velocity lower/upper wall
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Theory

For each computed potential line, the wall velocity can be estimated as follows

$$\bar{V} = l/n \quad (1)$$

and the curvature of the mean line by

$$\bar{k} = \frac{d\theta}{ds} \quad (2)$$

Subroutine WALLV (Cont'd)

Then define

$$\phi = \frac{1 - \bar{K}/(2\bar{V})}{1 + \bar{K}/(2\bar{V})} \quad (3)$$

and the approximate velocity at the wall is given by

$$v_{UI} = \frac{2}{1 + \phi} \bar{V} \quad (4)$$

$$v_{LI} = \frac{2\phi}{1 + \phi} \bar{V} \quad (5)$$

Arc lengths S_{LI} and S_{UI} may be calculated using subroutine ARCL for the lower and upper walls defined by (X_{LI}, Y_{LI}) and (X_{UI}, Y_{UI}) . The linear interpolation is used with arc length as an independent variable to interpolate v_L and v_U from the table v_{LI}, v_{UI} .

Subroutine XFGRID

Object

Interpolate uniform to nonuniform grid

Options

None

Input Symbols

DDS	Mesh distortion parameter
KL	Number of output streamlines
Q1	Input coordinate data array

Output Symbols

Q2	Output coordinate data array
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Theory

If IXFG option is turned on, only this subroutine is called by the main program CDUCT. This subroutine reads in input coordinate file from unit IUUNIT, interpolates the Q1 array with KN uniformly spaced streamlines to obtain the Q2 array with KL nonuniformly spaced streamlines and stores the output on unit INUNIT.

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